Chapter

Effusive Monogenetic Volcanism

Hugo Murcia and Károly Németh

Abstract

The study of monogenetic volcanism around Earth is rapidly growing due to the increasing recognition of monogenetic volcanic edifices in different tectonic settings. Far from the idea that this type of volcanism is both typically mafic and characteristic from intraplate environments, it occurs in a wide spectrum of composition and geological settings. This volcanism is widely known by the distinctive pyroclastic cones that represent both magmatic and phreatomagmatic explosive activity; they are known as scoria or spatter cones, tuff cones, tuff rings, maars and maar-diatremes. These cones are commonly associated with lava domes and usually accompanied by lava flows as part of their effusive eruptive phases. In spite of this, isolated effusive monogenetic emissions also appear around Earth's surface. However, these isolated emissions are not habitually considered within the classification scheme of monogenetic volcanoes. Along with this, many of these effusive volcanoes also contrast with the belief that this volcanism is indicative of rapidly magma ascent from the asthenosphere, as many of the products are strongly evolved reflecting differentiation linked to stagnation during ascent. This has led to the understanding that the asthenosphere is not always the place that directly gives rise to the magma batches and rather, they detach from a crustal melt storage. This chapter introduces four singular effusive monogenetic volcanoes as part of the volcanic geoforms, highlights the fact that monogenetic volcanic fields can also be associated with crustal reservoirs, and outlines the processes that should occur to differentiate the magma before it is released as intermediate and acidic in composition. This chapter also provides an overview of this particular volcanism worldwide and contributes to the monogenetic comprehension for future studies.

Keywords: lava dome, couleé, small-shield, lava flow

1. Introduction

Monogenetic volcanoes (typically $\leq$1 km^3 and $\leq 10^2$ years) are usually distinguished as dominantly formed by either magmatic or phreatomagmatic explosive activity and accompanied effusive processes. The magmatic explosive eruptions typically build scoria or spatter cones, while explosive phreatomagmatic eruptions characteristically form tuff cones, tuff rings, maars and maar-diatremes [1]. Associated with either activity, effusive emissions forming lava domes and lava flows are also common; consequently, these products are part of the mentioned volcanic edifices [2–4]. Frequently, individual effusive monogenetic emissions are also released into the Earth's surface, thus forming exclusively, or dominantly, effusive monogenetic volcanoes (e.g. [5]). In spite of this, they are usually not part of the monogenetic classification schemes (e.g. [1, 6, 7]), although many have been widely studied (e.g. [8–16]; among many other studies).

Lava domes in general have been mostly described as part of eruptions in polygenetic, intermediate to acidic volcanoes (e.g. [17]). From there, several types have been defined. Based on the growing mechanism, they are either endogenous whether they expand by intrusion of new magma or exogenous whether they enlarge by extrusion of it [18]; they are also called cryptodomes whether the magma did not reach the surface [19]. Furthermore, based on the geoform, they have received different names such as tortas, platy, axisymmetric, lobate, spines or peléean-type, upheaved plugs, viscous coulées lava streams, among others [17, 20–22]. As minor centers (i.e. as monogenetic volcanoes), the only classification that exist for our knowledge, is that outlined by De Silva and Lindsay [23] who grouped them in: 1) lava domes or tortas, 2) coulées, 3) peléean, and 4) upheaved plugs, based on their morphology. Individual monogenetic lava flows, in addition, are not part of this or any other classification scheme with the exception of the scutulum, low shields or small-shields (cf. [24, 25] that are mentioned by De Silva and Lindsay [23] within the mafic monogenetic volcanoes classification.

It is worth mentioning that the concept of "monogenetic" volcanism has even been considered in association with 1) Large Igneous Provinces (LIPs) that are overwhelmingly effusive, but formed in very short period of time in single flare ups [26], or 2) effusive dominated fields that are smaller than typical Large igneous provinces but significantly bigger than a "normal" monogenetic field [25]. In this work, however, we refer to small-volume monogenetic volcanoes, understood as small magma batches reaching the surface dispersed and episodically.

We herein propose the expansion of the existing monogenetic classification scheme after including the effusive volcanoes based on the above mentioned. This classification is based on their geoform, similarly to the explosive volcanoes. Furthermore, we provide a framework of the processes that act during the magma ascent and cause differentiation to produce intermediate to evolved volcanic products. Thus, we outline magmatic plumbing system options, which include crustal magma reservoirs as zones for detaching magma batches. Finally, we provide an overview of this particular poorly known volcanism worldwide, contributing to the monogenetic comprehension for future studies.

2. Effusive monogenetic volcanoes

The way that magma is monogenetically released to the Earth surface is related to the internal magma dynamic that occurred in the last dozens of meters [27]. It also depends on the form and dimensions of the conduit with the ascending magma. Whether the magma encounters water en route, a process known as MFCI (Molten-Fuel Coolant Interaction) occurs and therefore, it drives the eruption [28, 29]. In this case, the eruptive style depends mostly on the amount of water that the magma encounters [30] and the lithology where this water (usually an aquifer) is stored (e.g. sediments vs. fractured metamorphic rocks) (e.g. [31–33]; this last also associated with the easiness for the water to be released. However, whether the magma reaches the surface without any interaction with water, the eruption may occur in two ways: 1) explosive, whether the magma is fragmented by the volatiles dynamics (i.e. exsolution, nucleation, growth and coalescence) associated with pressure decreasing, or 2) effusive, whether degassing is effective, linked to bubbles interconnection avoiding the magma fragmentation [34]. The first eruptive manner builds scoria cones (e.g. the historical Jorullo [35–37] and Paricutín volcanoes in México [38]), while the second one produces lava bodies (e.g. The Villamaría-Termales Monogenetic Volcanic Field in Colombia; [5]). As previously mentioned, these emissions are commonly part of the explosive activity forming any kind of pyroclastic cone; however, they can also dominate and create individual effusive volcanoes (**Figure 1**). Because of this, we propose here these effusive products as part of a monogenetic volcano classification scheme and add them to those produced by magmatic activity (**Figure 2**). Accordingly, we propose to distinguish them between lava domes, coulées, small-shields and lava

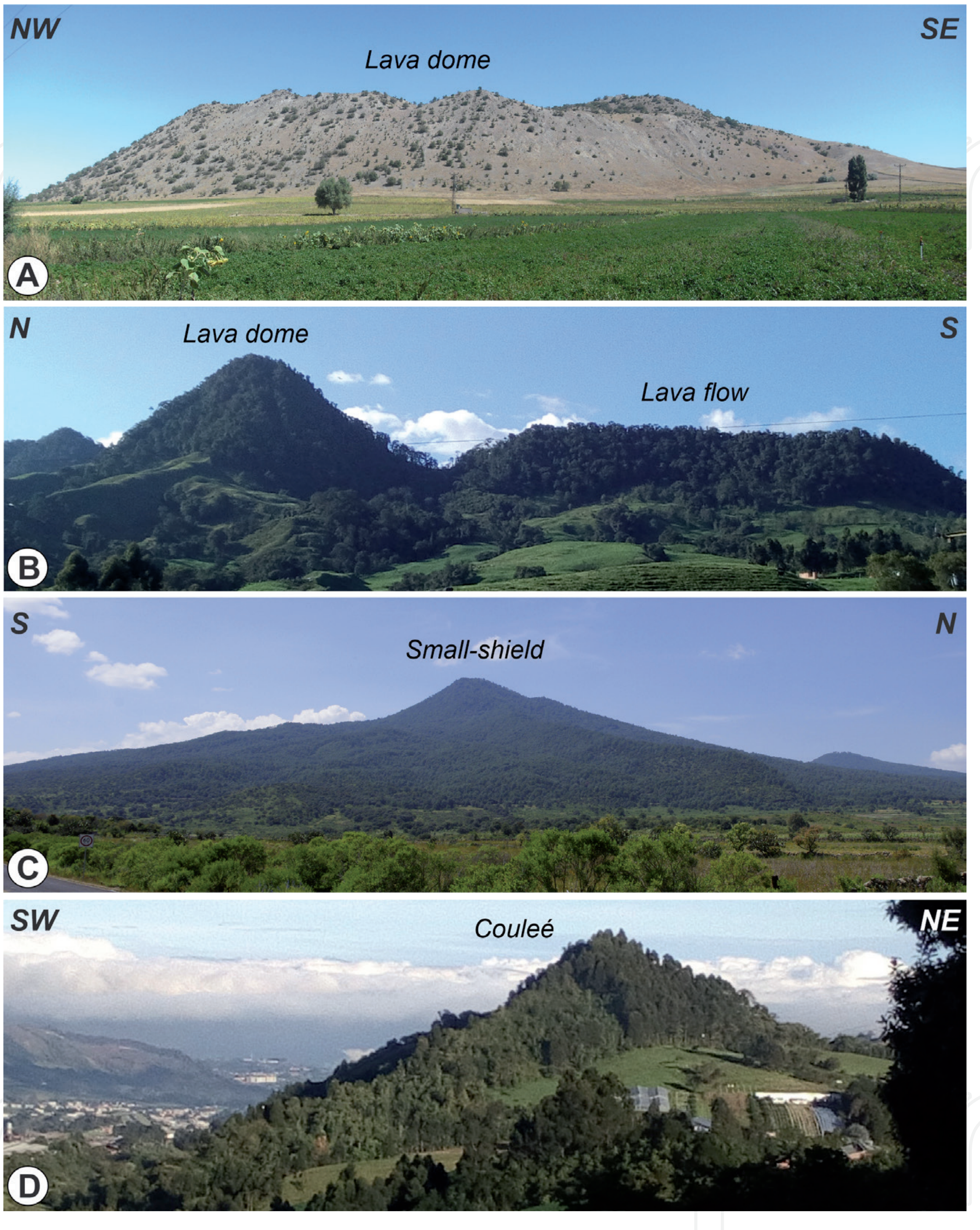

Figure 1.
Effusive monogenetic volcanoes. (A) Güneydag lava dome in Anatolia, Turkey; (B) Victoria lava dome and Victoria lava flow in Manizales, Colombia; (C) El Bosque small-shield in Morelia, México. (D) Tesorito couleé in Manizales, Colombia.

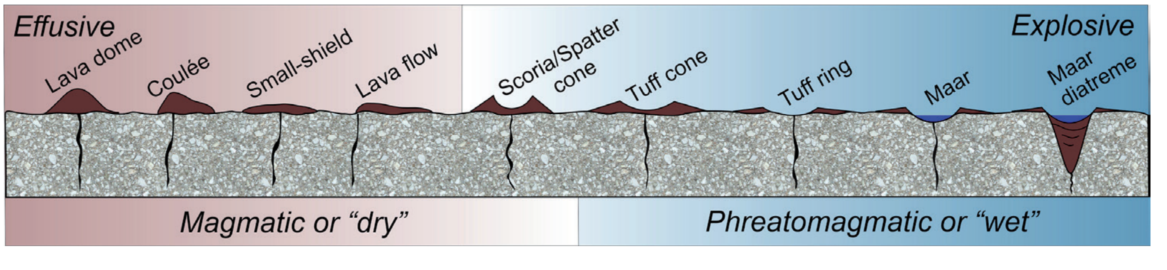

Figure 2.
Classification scheme of monogenetic volcanoes and their relationship with their eruptive style.

flows based on their geoform. The construction of every volcano is linked to the internal dynamics of the magma, but also to the form and dimension of the ascending conduit, the interaction of the conduit with the surface, and the topography where the magma is released. Every factor should be in-depth investigated. An overview of these elements is the topic of the following sections.

2.1 Evidences of internal dynamics

Coherent lava bodies of effusive monogenetic volcanoes have usually a glassy groundmass, which is the evidence of the rapid cooling when magma reaches the surface (**Figure 3A**). Commonly, the magma hosts phenocrysts (i.e. crystals greater than 0.5 mm) and microphenocrysts (i.e. crystals between 0.5 and 0.05 mm), although they do not dominate in the products. Occasionally, when the magma reaches the surface, decompression triggering solubility decreasing, oversaturation and degassing, induces crystal nucleation and therefore growing of multiple small crystals [39]; if these crystals can be distinguished in type, they are called microliths (usually between 50 and 5 μm) and the groundmass can be defined as microcrystalline if they dominated (**Figure 3B**), on the contrary the crystals can be called nanoliths (<5 μm) and the groundmass denominated as cryptocrystalline (**Figure 3C**). This crystal nucleation, along with temperature, composition (mostly SiO_2 but also MgO content) and dissolved volatiles (mostly H_2O but also CO_2), are the factors controlling the magma viscosity and somehow the volcano that is built (i.e. a lava dome, couleé, small-shield or lava flow). The higher the crystals and silica content, the higher the viscosity [39]; so, these magmas tend to form lava domes or couleés. On the contrary, small-shields and lava flows are related to low amount of crystals and low silica. Magma temperature tends to indicate relative low values in lava domes and high values in lava flows, while volatiles have a special behaviour [39]: their content is higher in viscous, high-silica magmas, but at the same time they keep viscosity lower; therefore, under a similar composition, a rapid degassing yields a lava dome formation, while a slow degassing leads to a lava flow geoform. Overall, slow ascent times are related to lava domes, while fast ascent times to lava

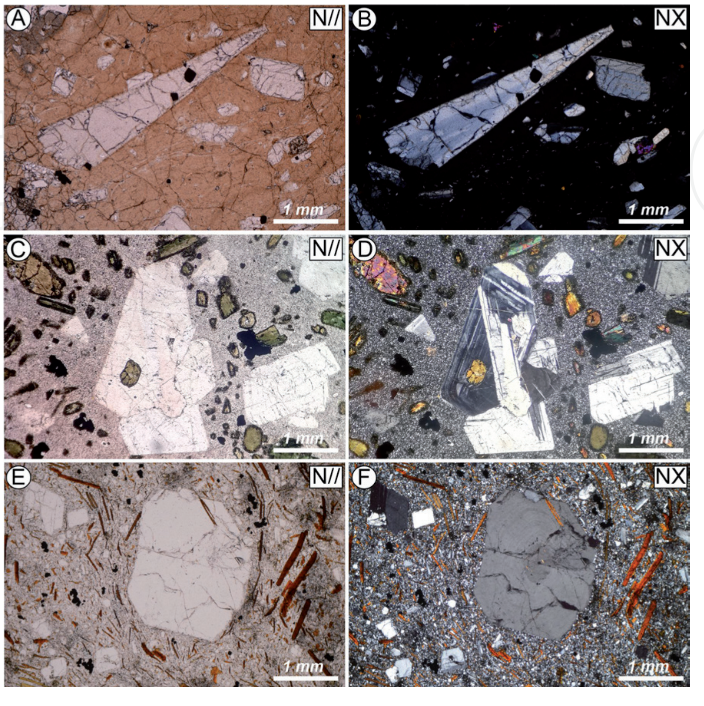

Figure 3.
Groundmass in effusive monogenetic products. (A, B) Glassy groundmass. (C, D) cryptocrystalline groundmass. (E, F) microcrystalline groundmass. Parallel nichols to the left, crossed nichols to the right.

flows. The relationship between the mentioned elements, however, are somehow circular or themselves dependent, and consequently without a linear relation. Thus, although the groundmass and the major crystals are evidence for the dynamics of magma propagation during ascent, from our experience, no direct relationships can be drawn between any of the elements vs. the volcanoes, even in a thin section study of the eruptive products under the microscope. This is worth mentioning because it explains why the definition of these volcanoes is purely dependent on the geoform and do not consider, for instance, petrographic characteristics. In spite of this, we consent some approaches that can be made from a rock. For example, an increase in decompression rates results in (1) bubbles and crystals with smaller sizes, (2) a lower crystallinity and thus higher glass fraction, and (3) a higher abundance of unstable hydrous phases [17, 40]. This may help as a starting point for subsequent studies when a rock from effusive monogenetic volcanoes is analysed.

2.2 Magma conduit and topography

Monogenetic effusive volcanoes are related to physical elements such as the conduit form and dimension, and the interaction with the surface, but also to the topography where the magmas are released. Thus, the volcanoes can be formed through a cylindrical vs. a fissural conduit and in a flat vs. a hilly topography. This complex emplacement can deviate the resulting geoforms from what we normally would expect. For instance, a lava flow volcano that could be linked to a low viscosity magma, could be really the result of a high viscosity magma released and emplaced through a long fissure in a flat topography; also a dome-like geoform that could be linked to high viscosity magma, could be really the result of a lava-type, low viscosity magma, released in a valley or basin that limited its movement. A more complex circumstance could also occur when the magma solidifies forming barriers for subsequent melt to come out, although clearly this situation would not play any role in large volume of magma outpourings. Thus, the upper dozens of meters of the conduit geometry in turn related to the shape of the crater and the magma rheology will be very important in the resulting landform type. Because of the obvious complexity and due to most of the times the construction of the volcanoes is not witnessed, the proposed classification scheme is based on geoforms, thus avoiding terminology complication associated with the source. **Figure 4** details the ideal geoforms when related to conduit and topography.

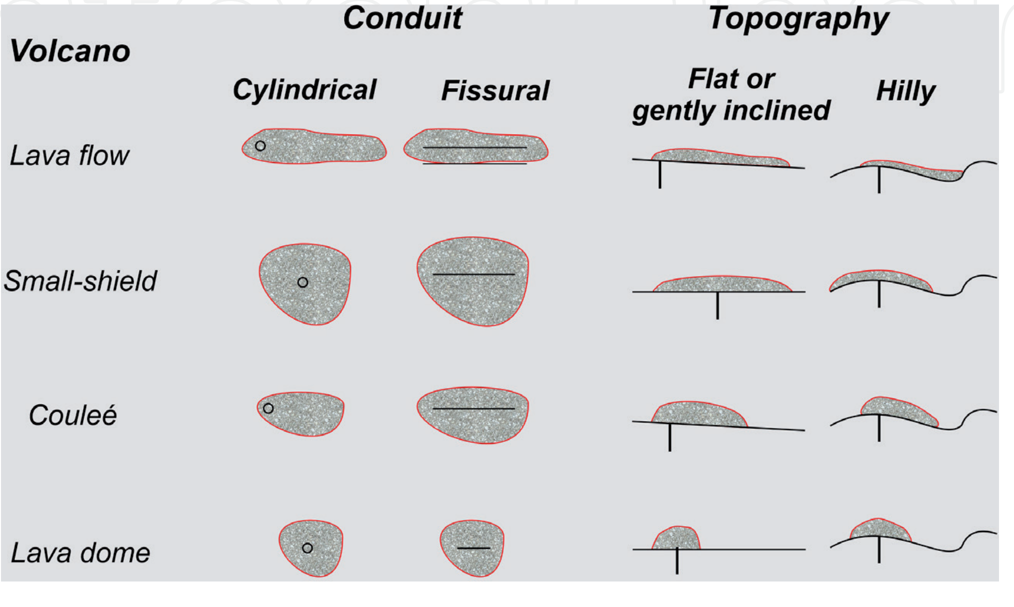

Figure 4.
Volcanic geoforms vs. ascent conduit type and emplacement topography.

2.3 Magma releasing

Magma fragmentation is associated with bubble nucleation and growth. Thus, fragmentation occurs when the gas volume fraction reaches a critical value, i.e. when the magma changes from a liquid with bubbles to a medium of bubbles with liquid [40]. Bubbles, in turn, are a function of water diffusivity and melt viscosity during magma ascent and decompression; diffusivity is important for the feeding of the bubbles, while viscosity for allowing their growing [39]. Considering high efficiency of bubbles feeding and growing in a magma, it is possible to state that: a rapid decompression linked to a relative high ascent time, produces a high rate of bubbles nucleation, expansion and coalescence, and therefore a magma fragmentation to form a scoria/spatter cone. On the contrary, a slow decompression linked to a relative low ascent time, produces a low rate of bubbles nucleation; this yields to expansion, coalescence, channelling and the generation of a permeable network, which allows outgassing; the result is a magma reaching the surface without being fragmented, thus forming an effusive monogenetic volcano. In conclusion, effusive volcanoes in general are indicative of slow ascent times, at least, in the last part of their journey before reaching the Earth's surface.

3. Magma evolution

Although monogenetic volcanism is widely known as part of basaltic magmatic systems (e.g. [7, 27, 41], it is also known as accompanying more complex mafic or even intermediate to acidic systems [42–48], thus indicating magmatic evolution during ascent. This evolution points to significant magma differentiation necessarily associated with low ascent rates or even magma crustal stagnation, and therefore evolution through processes such as fractional crystallisation and assimilation. This evolution is evidenced in the erupted magmas by trails such as: 1) the common presence of significant amount of intermediate plagioclase and mainly amphibole that requires relatively low magma temperatures to crystallise (<1000°C) (e.g. [10, 49, 50], 2) the common presence of crustal xenoliths and xenocrysts indicating time for incorporation and partial or total dilution (e.g. [8]), 3) the almost ubiquitous wide range of liquid compositions of glass within the same products indicating microscale magma interaction/evolution while minerals are forming; this yields heterogeneous portions of magma (e.g. [51]), 4) the strong variation of trace elements at constant SiO_2 or MgO values within the same volcanic field (e.g. [10]), and 5) the diverse isotopic ratios indicating strong assimilation from the basement, also within the same volcanic field (e.g. [8, 26]). Magma mixing and self-mixing are possible additional processes linked to the magma evolution (e.g. [13, 43, 52]). Evidences of these are mineral disequilibrium textures (e.g. coronate, embayment, sieve, skeletal), reverse compositional zoning in minerals others than plagioclase (e.g. [53]), and also glass compositional differences in the same products [51]).

4. Magmatic plumbing systems

A magma plumbing system under a monogenetic volcanic field can be understood as a network of interconnected dikes and sills that reach the surface in several points via different pathways [54]. Usually, these fields are understood as originated by magma reaching the surface directly from the asthenosphere in terms of weeks or months through simple conduits without any pattern [7]. This is evidenced in the very common primitive magmas and scattered volcanoes that characterise many volcanic fields (e.g. [55]). There is also a "common wisdom" that acidic compositions produce large monogenetic volcanoes only and that most of these volcanoes are related to magma chambers feeding polygenetic volcanoes [1] due to stagnation in the crust makes the magma batches un-eruptible [7]. However, typical (in volume) monogenetic volcanoes, which are intermediate to acidic in composition, are commonly forming monogenetic fields, thus indicating: 1) "normality" rather than "rarity", and 2) stalling magma zones en route without cooling and crystallisation inhibiting the eruptivity. This stagnation has been evidenced as occurring within the lithosphere (e.g. [9]), particularly in the upper mantle-lower crust limit, or within the crust itself (e.g. [10, 12, 56], occasionally leaving small intrusive igneous bodies underneath the surface (e.g. [57]). This stagnation forming melt storage zones is a common geological explanation for many evolved monogenetic volcanic fields on different tectonic settings on Earth (e.g. [8, 11, 13, 14, 43, 52]). Thus, magmas coming to the planet surface directly from the asthenosphere tend to be mafic, while those coming from crustal melt storages tend to be either intermediate or felsic (**Figure 5**). Already near the surface, the eruptive style is driven by the internal magma characteristics but also by the external conditions linked to the lithology and the environment [27]. If the magmas do not reach the surface, they could form what would receive a name such as "monogenetic plutonic field." Monogenetic volcanoes can also be associated with polygenetic volcanoes and therefore with magma chambers; in this case, the composition of the products is fully related to the processes involved in that chamber (**Figure 5**).

4.1 Examples

A well-known place on Earth where effusive monogenetic volcanoes are located is the Altiplano-Puna Volcanic Complex [58] in the Central Volcanic Zone in South America [59]. In this place, several of these volcanoes have been identified, usually

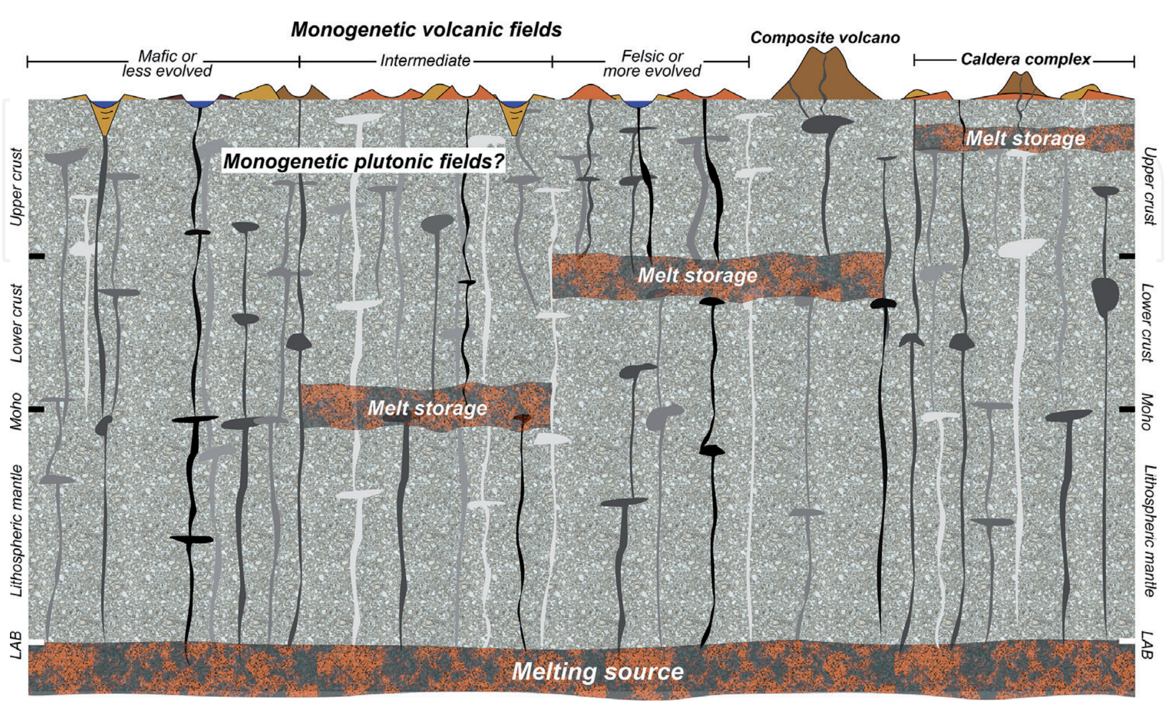

Figure 5.
Schematic framework of magmatic plumbing systems for monogenetic volcanic fields. LAB: Lithosphere-Asthenosphere Boundary. Not to scale.

with intermediate compositions (e.g. SC2 shield-like volcano; [8]), and occasionally related to post-caldera activity (e.g. El Viejo Couleé, [60]). After several studies, it has been proposed partial melting zones linked to magma stagnation either around the Moho boundary or within the continental crust (e.g. [8, 10]).

The French Massif Central is another widely known example where effusive monogenetic volcanoes exist. The iconic Puy de Dóme [61] along with other effusive and explosive volcanoes (e.g. [62, 63], form the Chaine des Puys volcanic field [64]. Volcanoes from this field have been interpreted as formed by magma detached from a melt storage or reservoir in the upper crust, where crystal fractionation plus self-mixing and minor crustal contamination occur (e.g. [13]).

In the west part of the Arabian shield [42, 52, 65], where mostly lava flows as effusive monogenetic emissions have occurred through time [66, 67], recent investigations have proposed a plumbing system composed of a melting region in the asthenosphere with magma stagnation zones in the upper part of the lower crust (e.g. [14]). Similarly, in the Colombian Andes, recently identified intermediate to acidic effusive monogenetic volcanoes forming volcanic fields have been linked to a plumbing system that include a magmatic reservoir located in the upper part of the lower crust [12]. This melt storage zone gives rise to the monogenetic volcanoes, but also to at least 10 composite volcanoes that exist in a 140 km-long volcanic chain.

Finally, it is important to mention the widely known Michoacán-Guanajuato Volcanic Field in México [68–71], where more than 1000 monogenetic volcanoes have been identified [72]. Lava domes, small-shields and lava flows are characteristic of there (e.g. [15, 16, 73]. Although most of the volcanoes seems to be mafic to intermediate (between 50 and 62 wt.% in SiO_2; [72]) some reach up to 69 wt.% (e.g. [11]), thus invoking crustal stagnation linked to evolution. Some others, however, seems to be the result of magmas detachment directly from the asthenosphere (e.g. [74]), as it also seems to occur in the Acigöl rhyolite field in Anatolia, Turkey [48], where interesting effusive volcano geoforms exist.

5. Conclusions

Small, short-lived and dispersed effusive monogenetic volcanoes are common in different tectonic settings. They can be mafic but also intermediate to silicic in composition and grouped in field arrangements with their explosive counterparts. The volcanoes are common in convergent plate margins like the Andean arc, but also in orogenic regions like Anatolia or intracontinental settings like Arabia or Sudan. Crustal stagnation is common and eventually ready to act as a “source of melt” in small volume and distinct release; this leads to magmatic plumbing systems related to sort of extensional tectonic, small-scale, regimes acting as “windows” for melt releasing, even in compressional regional settings.

In the monogenetic mafic systems, the chemical signatures most likely reflect the source processes (i.e. magma generation, source depth, melting rate, among others), however, in effusive, commonly silicic systems, these primary features are overprinted by the shallow storage and melt segregation signatures. This makes somehow more complex the understanding of the magma evolution. This adds to the fact that the recognition of such silicic effusive monogenetic volcanic systems in the geological record is not easy and requires some petrologic work and the understanding of the overall stress-field.

Finally, we emphasise that effusive monogenetic systems as a conceptual framework could work in volcanic fields overwhelmingly effusive, with a huge volume of effusive products or even classified as large igneous provinces.

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